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EARTH-SPACE TELECOMMUNICATION OF THE FUTURE

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Research Laboratories
HUGHES AIRCRAFT COMPANY

EARTH-SPACE TELECOMMUNICATION OF THE FUTURE

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ABSTRACT

The future of earth/space communication is forecast on the assumption that present state-of-the-art limitations can be overcome, eventually, but that the laws of nature will endure. Space repeater stations in stationary orbit appear preferable to lunar repreaters and should have dual use for earth/earth and earth/space relaying. In the latter case, interplanetary propagation delays will constrain operational practices, precluding dependence on earth-made military decisions. Beyond the atmosphere, higher frequencies and perhaps lasers will become advantageous when acquisition and tracking improves. Earth/earth relaying will use most of the repeater capacity, which may exceed a half-million voice channels. Such large-scale use may be an international mixture of military and non-military traffic and should be multiple access, with hundreds or thousands of earth stations interconnecting through each relay satellite as if it were an exchange in orbit. Inexpensive fixed antennas will lower the station fixed costs, making light-traffic stations economically attractive. Mobile communication is possible but may be constrained by difficulty of sharing channels with surface radio services. Reliability problems are certain to diminish and these tremendous future satellites may be manned, or at least be serviced periodically. A combination of features will diminish the jamming vulnerability below the destruction cost. Hence, a future Air Force mission may be the defense or replacement of our orbital communication centers.

EARTH-SPACE TELECOMMUNICATION

OF THE FUTURE

This paper will hazard a forecast concerning earth-space telecommunication systems of the future, emphasizing certain aspects which are of Air Force interest.

In all technological forecasting, it is essential that we distingguish between state-of-the-art limitations and the physical limitations imposed by the laws of Nature. The former can be overcome, given enough time, money, and intelligence. Trying to repeal or violate the laws of Nature is futile; one must accept them and learn to live with them. For example, it would be futile to attempt to increase the velocity of electromagnetic propagation and thereby reduce the time delays in interplanetary communication. Operating practices must be adjusted to make the best of them.

At interplanetary distances, propagation delays will range from several minutes to hours, as shown in Fig. 1. These time delays certainly will constrain communication operating practices and probably will influence tactical concepts of space warfare. An engagement at these distances can not be controlled or be made dependent upon a sequence of decisions from the earth because the delays would be fatal. The human astronaut can make snap decisions, assisted perhaps by an onboard computer. He must have freedom of action, i.e., freedom from communication delays. Nonetheless, communication always will be necessary; therefore we will examine some of the salient features and possible problems of far-future earth-space communication systems. It will be postulated that most of today's state-of-the-art limitations will have been overcome by this far-future date.

Let us first review some physical limitations, such as space transmission loss and the consequent power requirements. Assuming that non-directional unity gain antennas were used at both ends, Fig. 2 shows the effect of frequency and path length on the path loss, expressed in decibels. These hundreds of decibels tend to be meaningless until related to power. Assume that the minimum useful received power is 10^{-15} W*, or a micro-micro milliwatt; 150 dB less than one watt. The power scale in Fig. 2 then shows one watt as corresponding to 150 dB, with 300 dB corresponding to a mega-mega kilowatt. In comparison, the total power generated in the United States is only about 185×10^{6} kW. Only stars like our sun can generate and radiate useful power in all directions to astronomical distances! Man needs to concentrate his feeble power with lenses or directive antennas. When directivity cannot be used, Fig. 2 shows that it is advantageous to use low frequencies.

*This would correspond, for example, to a signal having a carrier-to-noise ratio of only 14 dB and only 10 kc bandwidth in a nearly earth-temperature (300°K) receiver.

When antennas or lenses of fixed aperture can be used, the gain of each antenna is proportional to the square of its aperture measured in wavelengths, hence it is proportional to frequency squared. Figure 3 assumes apertures of 10 and 100 ft, for purposes of illustration. Earth antenna apertures have exceeded 100 ft, at least at the lower microwave frequencies, but using such an antenna or even a 10-ft antenna on a space station or space craft is beyond the present state of the art. Moreover, at optical (laser) frequencies, one recognizes that the 16.6-ft Palomar reflector would be an awkwardly difficult payload! Nonetheless, Fig. 3 shows the loss reduction achieved by increasing the frequency when using these fixed aperture antennas.

Of course, large antenna apertures lead to increasingly narrow beams. The beamwidth is inversely proportional to the aperture-frequency product, as shown in Fig. 4. It is difficult to track satellites with today's large microwave antennas whose beamwidths only approach 0.1°. Lasers raise the frequency about five orders of magnitude, but they are not apt to be used with 100-ft lenses! One-foot apertures are more realistic and, thusfar, beamwidths are limited by lack of phase coherence across the aperture. Beamwidths of 2×10^{-4} rads (0.01°) seem typical of today's laser art*; this being little more than an order of magnitude beyond the microwave art. How far and how rapidly both arts will advance is a matter

* "Project Luna See," Proc. IRE, July 1962, pp. 1703-4, Correspondence from L. D. Smullin and G. Fiocco.

of conjecture and one which is immaterial to this study. Whether microwaves, millimeter waves, or optical waves are used, obtaining greater gain means narrower beams and worse acquisition and tracking problems, nonphysical problems which this study neglects as being solvable - eventually.

It appears that frequencies well above 10 Gc are potentially better for deep space communication, except for the physical limitations of atmospheric absorption and scattering, especially through heavy rain clouds. For reliable space communication these frequencies should be used outside of the earth's atmosphere, from an orbiting space station. Should such a station be on the moon or should it be an artificial satellite? SURVEYOR, APOLLO, and subsequent programs may define the zoning restrictions on lunar real estate. However, there are two physical arguments against a lunar astrocommunication center which favor an artifical satellite: the moon is too big and too far. One would need three or four such lunar centers to cover all directions, and the 2.6-sec round-trip delay precludes normal two-way conversation. Speakers try to say everything before stopping, as they do with a push-to-talk circuit. On the other hand, the moon would provide a highly stable platform.

I favor an artificial satellite, particularly a stationary satellite. Let's call it SYNCOM-N, to avoid suggesting a date. A stationary satellite has many potential advantages for communication, but only a few need be mentioned: (1) As an astrocommunication center, the stationary satellite has the advantage of being fixed in relation to the rotating earth. Knowing earth time, the astronaut would know the position of each of several such centers. (2) The distance between two diametrically opposite stationary satellites is nearly seven times greater than the earth's diameter, so it would provide a better baseline than is possible on the earth. (3) The earth antennas would have fixed reflectors, slightly steerable from their feed point. If made of concrete, earth supported, such antennas will be cheap and relatively hard. Figure 5 shows a 240-ft fixed reflector antenna, built in 1953 by the Naval Research Laboratory for approximately $100,000, which was used for the first voice moonbounce experiments.

These stationary satellites should not just be relay centers for astrocommunications. Since they are large, relatively expensive, and occupy stations in a desirable and eventually crowded orbit, they also should relay terrestrial communications on a large scale. Certainly, they should provide communication between the flight lines of the future. Additionally, they should link all other military and governmental communication centers. Perhaps they also should provide international common carrier service, even to many relatively small and isolated population centers. Such service might discourage jamming, as will be discussed later.

Any such satellite communication system needs "interconnectability" or multiple-access capability. Each earth station should be able to communicate directly with each and all of the satellite's hundreds of stations, much as if the satellite were a switching center. Stationary satellites have technical advantages for multiple-access systems, but there are related earth-station economic advantages which have greater importance.

The cost of an earth station can be separated into fixed costs, such as buildings and land, and "per-circuit" costs, such as for the circuit multiplexing equipment. If nonstationary satellites must be tracked, the set of large steerable antennas and their associated acquisition and tracking equipment constitute the controlling item of fixed cost, several million dollars.* Land, buildings, roads, etc., are apt to be in keeping with such costly antennas, so may add about another million dollars. The per-circuit costs of the transmitter multiplexing equipment, etc., are relatively low, i.e., only a few thousand dollars per circuit. Such a station must have <u>many</u> circuits to balance its costs. For example, at $5,000,000 plus $5,000 per voice circuit, a 1000-circuit station would cost $10,000,000 total or $10,000 total per circuit. For only ten circuits this would soar to $505,000 per circuit! Consequently, one prefers to use random-orbit satellites between <u>pairs</u> of high-traffic earth stations, as if these stations were connected by a cable.

How can we afford light-traffic stations for a multiple-access system? Trim their <u>fixed</u> costs! Use rugged <u>stationary</u> antennas with stationary satellites. A concrete or other earth-suppored antenna should cost less than 1% as much as a fully-steerable installation, say $20,000 for purposes of illustration. Other fixed costs may raise the total to $100,000,

*The TELSTAR horn-reflector antenna installation at Andover, Maine is reported to have cost $15,000,000, compared with about $1,200,000 for a 60-ft parabola. Even if diplexed, two antennas are needed for hand-over, plus a stand-by antenna.

equal to the per circuit costs of only twenty circuits. Even a single-circuit station would cost only $105,000; less than the cost of many HF stations. Hency, cheap fixed antennas and stationary satellites are the key to multiple access.

What about satellite costs? These will be about the same in either case, eventually. The total cost of many random-orbit satellites will be about the same as for the very few high-capacity stationary satellites.

The flight line of the future surely will need multiple-access communication: globally to all other flight lines and military centers and extraterrestrially to all spacecraft. Multiple access brings space communication to its users, rather than requiring many users to bring their traffic via surface communication to one of the few big earth stations. In short, multiple access will get space communication off the ground.

More specifically, what may this future system and its satellites be like? As technology advances sufficiently, large space stations should cost less per ton or per circuit than small ones. Also, a relatively large station should provide a better platform for laser communication with spacecraft and for the use of many pencil-beam earthward antennas. Figure 6 illustrates this concept, recognizing that it is currently impossible to know how such a station actually will appear.

How much traffic could one such repeater station carry? Figure 7 shows the microwave frequency bands which are being proposed for satellite communication. With the exception of two narrow bands, these would be shared with surface microwave communication systems. The shared bands total nearly 4 Gc. We will assume that 5 Gc is available at this future date, and that it is re-used ten times by pencil-beam antennas on each satellite - half for receiving and half for transmitting. This large repeater would have ample power, probably nuclear power, so today's spectrum-wasting, power-conserving wide-deviation FM would no longer be needed. Therefore, recognizing many difficulties, we assume single-sideband modulation, or its equivalent, with 5-kc average per voice circuit. One could handle the equivalent of 5 million voice circuits! This estimate may be high by a factor of ten, but even a half-million voice circuits per satellite is a bit staggering today. Of course, voice circuits are only a convenient expression for communication capacity, as telegraph circuits would have been to Samuel Morse. There will be television, digital data, and probably bandwidth-hogs which have not yet been invented. Nevertheless, there should not be a half-million military conversations, or its equivalent, per satellite. Hence, these satellite repeater stations also might carry international nonmilitary traffic, i.e., civilian traffic with virtually all nations within the third of the earth covered by each stationary satellite. Many such nations would be neutrals and their traffic would be so mixed with the total that it would be extremely difficult, if possible, for an enemy to jam just our military circuits without alienating the neutrals or even its allies.

In event of war, this satellite might become primarily a military communication facility with most of its unprecedented bandwidth made available for spread-spectrum or other AJ techniques. Additionally, the use of many very narrow earthward antenna beams will confer further jamming protection. Hence, it is believed that it will become more expensive to jam than to try to destroy such satellites. The defense or replacement of these communication satellites may become an important future Air Force mission.

Many people will be skeptical about the electronic unreliability of this enormous satellite repeater. COURIER failed in 18 days. The first Transatlantic cable also failed after a few days, but the first successful one, laid in 1854, was just recently retired from service - still operable. We can't expect TELSTAR to play for a hundred years, but it already has a good start toward one year, and subsequent TELSTARS should last 10 years or so. Reliability is only a state-of-the-art problem, though a vitally important one. Insofar as SYNCOM-N is concerned, we can dodge the reliability problem by postulating that it will be a manned repeater, or that it can be visited for periodic servicing. One should recognize, however, that it will become difficult for a laser to track a distant spaceship when a man moves around inside this orbital repeater station!

What about communication with aircraft, ship, and other mobile stations? Mobile communication via satellites will be possible, but at a price.

This price may include worse jamming problems and the inability to share frequencies with surface radio services. The mobile station is apt to be a "poor" earth station in terms of transmitter power, receiver sensitivity, and particularly in terms of antenna gain. Carrying a steerable 60-ft dish would degrade the performance of most aircraft - to state it mildly! Satellites will be able to transmit a sufficiently strong signal to aircraft, at least within a relatively narrow band, but such a signal also would interfere with surface radio receivers. Additionally, aircraft would fly over surface radio stations and thus create worse interference problems. Of course, if aircraft always fly sufficiently high and with a few other ifs, it may be possible to use frequencies well above 10 Gc, letting the lower atmosphere help protect surface communication. Such high frequencies reintroduce the antenna gain and tracking problems.

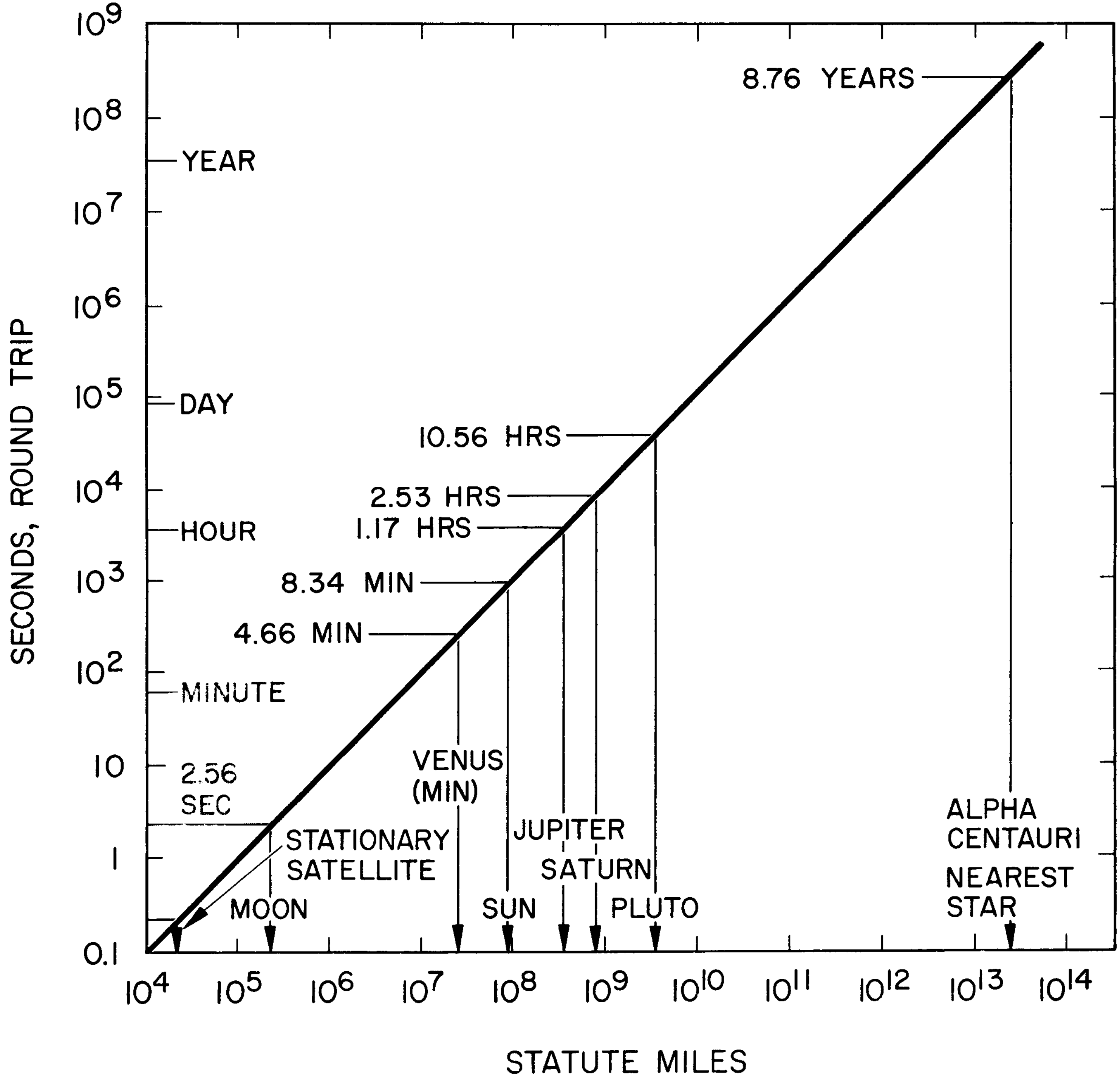
To illustrate this antenna difficulty, assume that the aircraft uses a 3-ft antenna aperture at 40 kMc. Its gain, beamwidth, and satellite tracking difficulty, even if the aircraft were parked on the ramp, would scale to be the same as with a 60-ft antenna used at 2 kMc. The area of this little antenna, and hence the power it could receive, would be reduced to 1/400, or by 26 dB. One can imagine the problems of tracking even a stationary satellite with such an antenna while flying in rough air and perhaps taking violent evasive action! Again, however, good tracking is only a state-of-the-art problem.

What about satellite communication with the polar regions? One limitation of stationary satellites is that their maximum visible latitude is 81-1/4°, and their useful latitude limit will be somewhat less. A second satellite orbit system will be required for polar coverage, say within 10 to 20° of each pole. This auxiliary satellite system can use a polar orbit of any altitude or it can use an inclined synchronous orbit of a sufficient altitude, as shown in Fig. 8. Such use of a second orbit introduces interorbit interference problems, unless separate frequencies are used. Polar stations would need to track such satellites, making us wish for a stationary polar satellite. This seems like another physically impossible wish, but not quite. If we are willing to accept other problems and costs, we <u>can</u> have the non-tracking and multiple-access advantages of a polar stationary satellite. All that is needed is enough satellites in the same polar orbit so that at least one always will be in the converging antenna beams above each pole. One obvious solution, with less obvious problems, is a polar belt of orbital dipoles, or needles, as shown in Fig. 9.

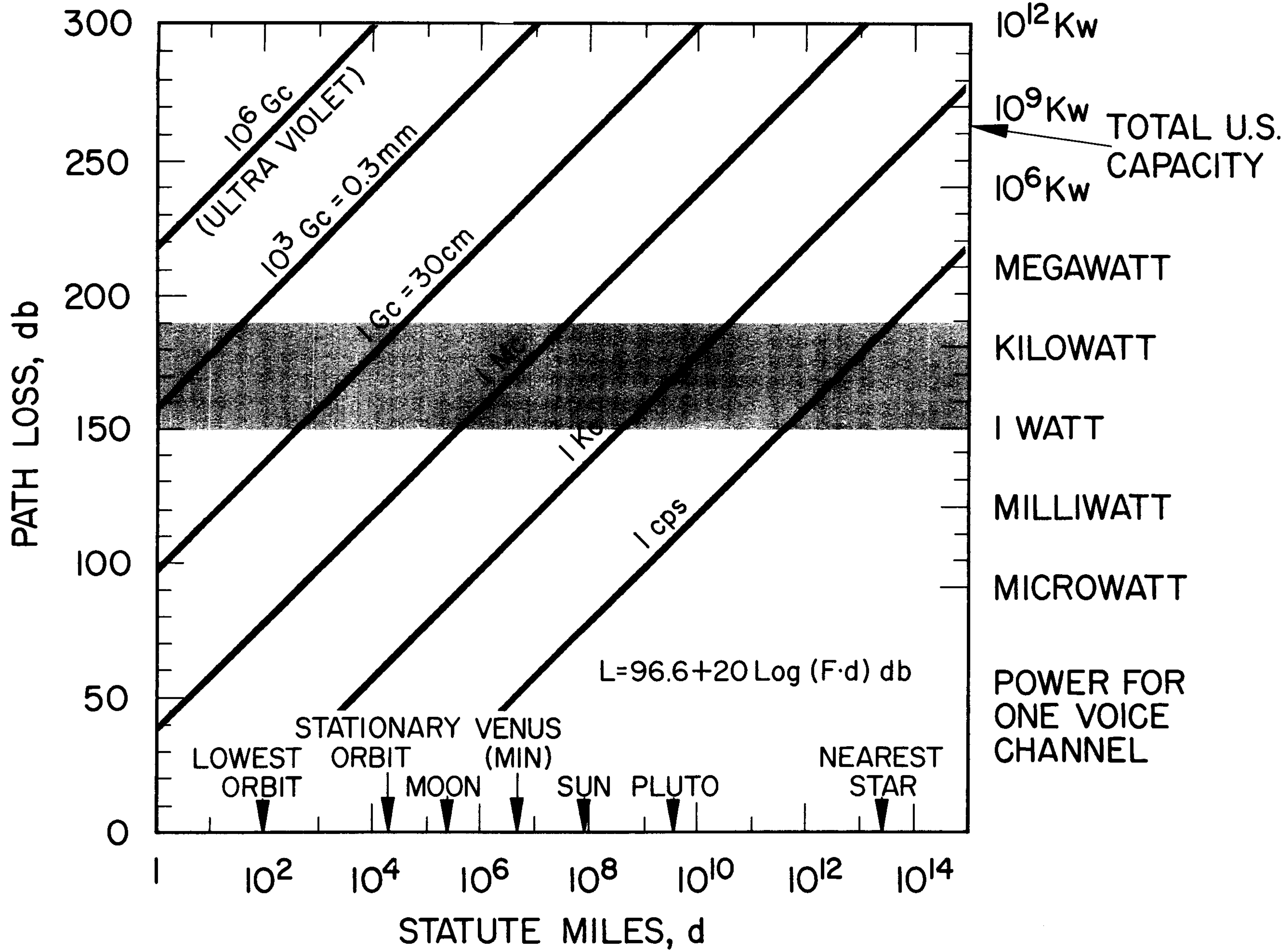
To conclude this discussion, one can see that space communication technology is certain to revolutionize prior concepts of communication, leading us to true global systems and on into extraterrestrial systems. Such systems someday may make 480L look as relatively simple and primitive as a rural telephone exchange! If such a system is to evolve logically, efficiently, and economically, and not via a sequence of quick-fix programs, we need to intensify today's studies of these systems of the future. We need to identify the possibilities and problems. We need to distinguish between the lasting physical problems and the state-of-the-art problems. We need to guide ourselves around the physical problems, or let them guide us, and plan past the other problems while they are being solved.

Predictions such as these are dangerous, especially in relation to their time scale and technical details.. However, a greater danger may lie in not trying to make such a prediction, or in not trying hard enough to follow a straight route toward the system which we see in the future.

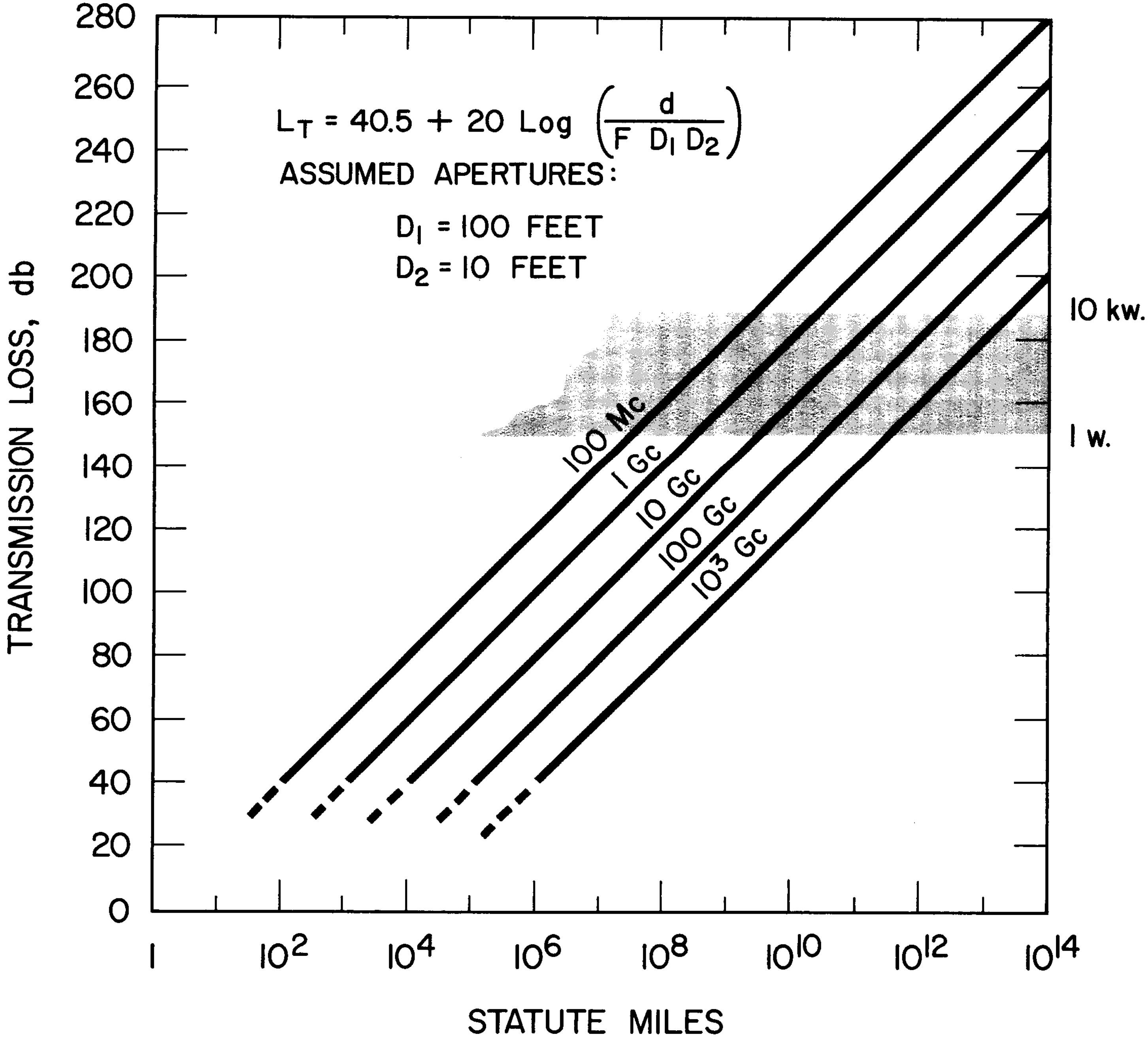
COMMUNICATION DELAYS PAUSE-TO-REPLY



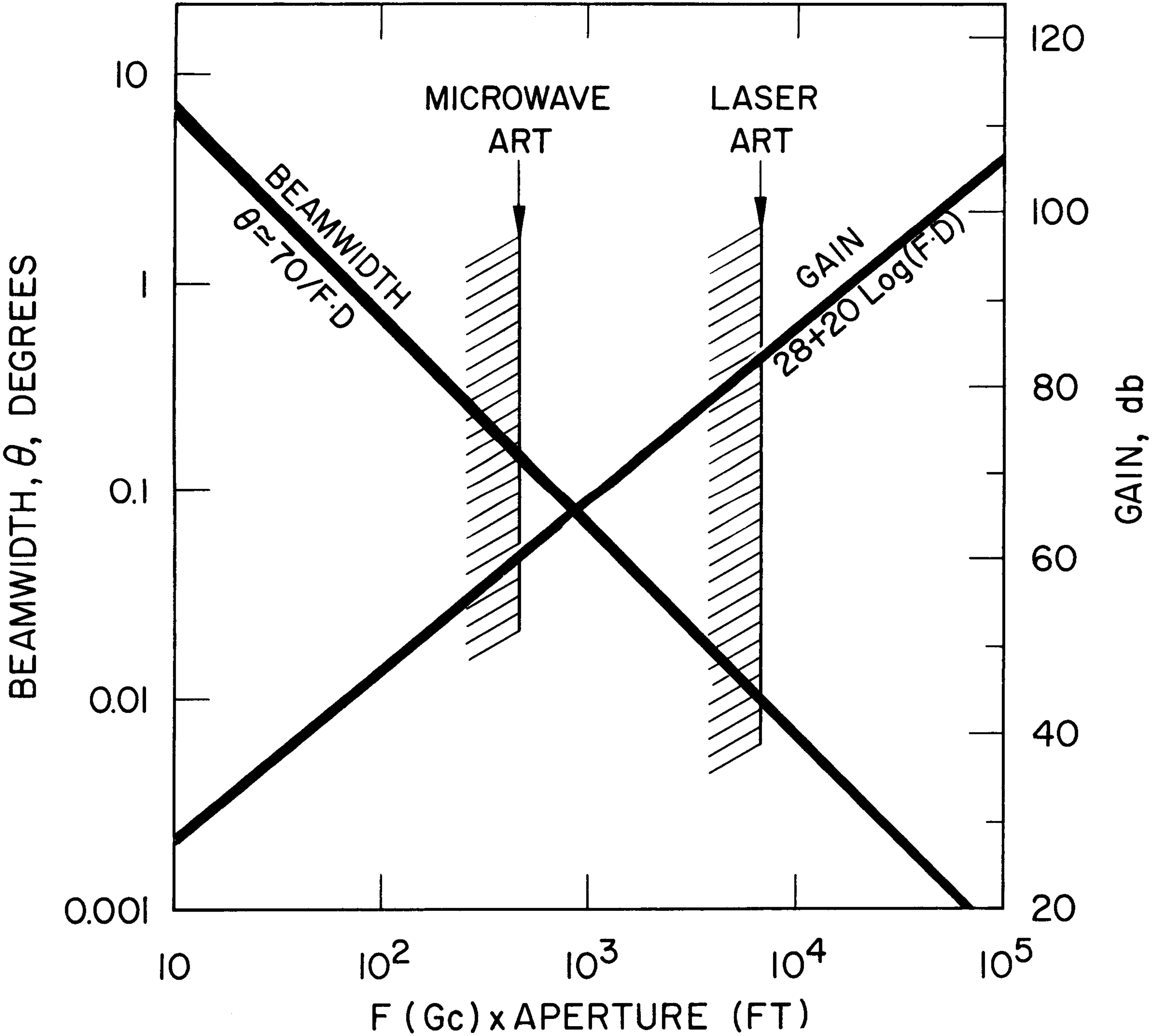
ISOTROPIC (UNITY GAIN) ANTENNAS

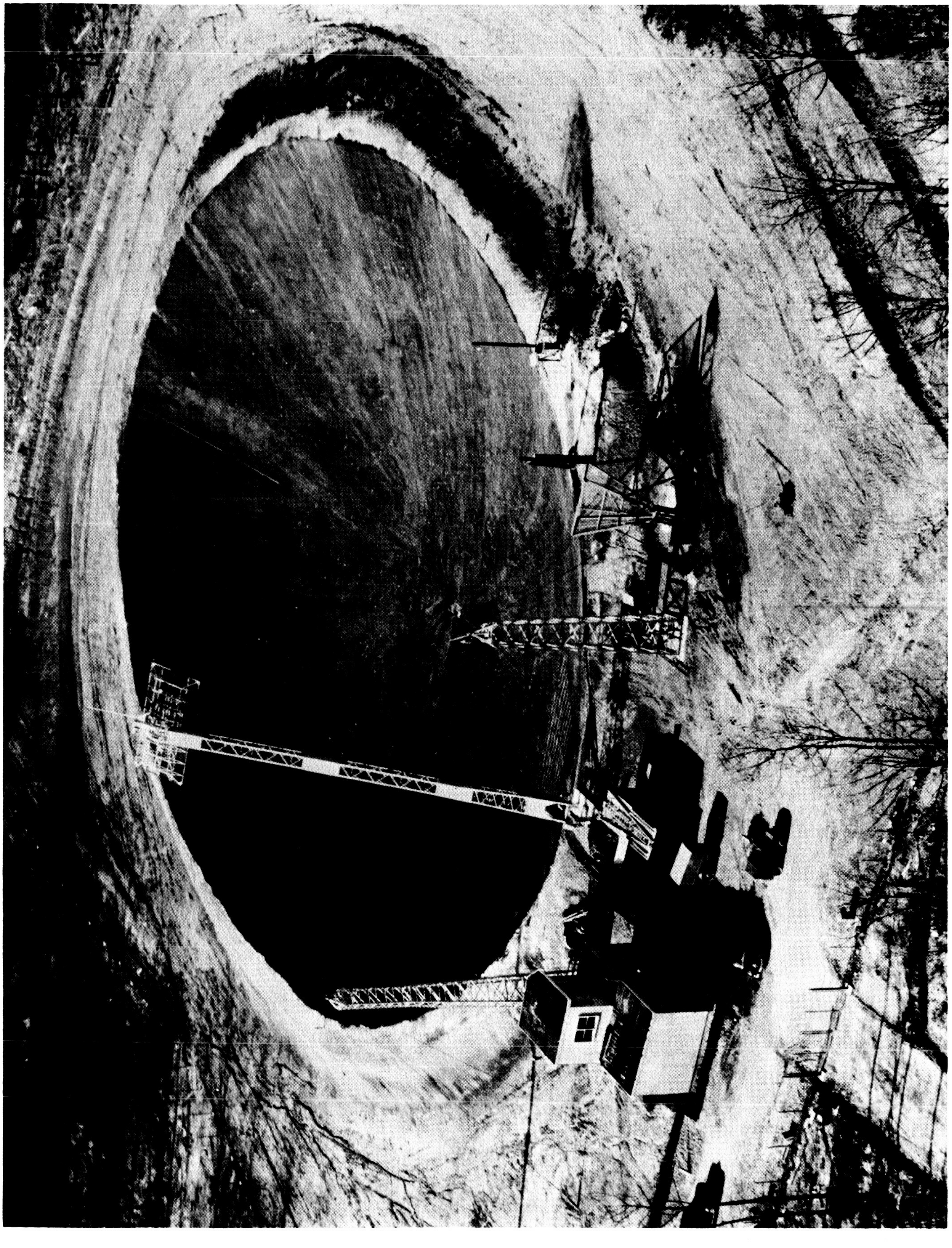


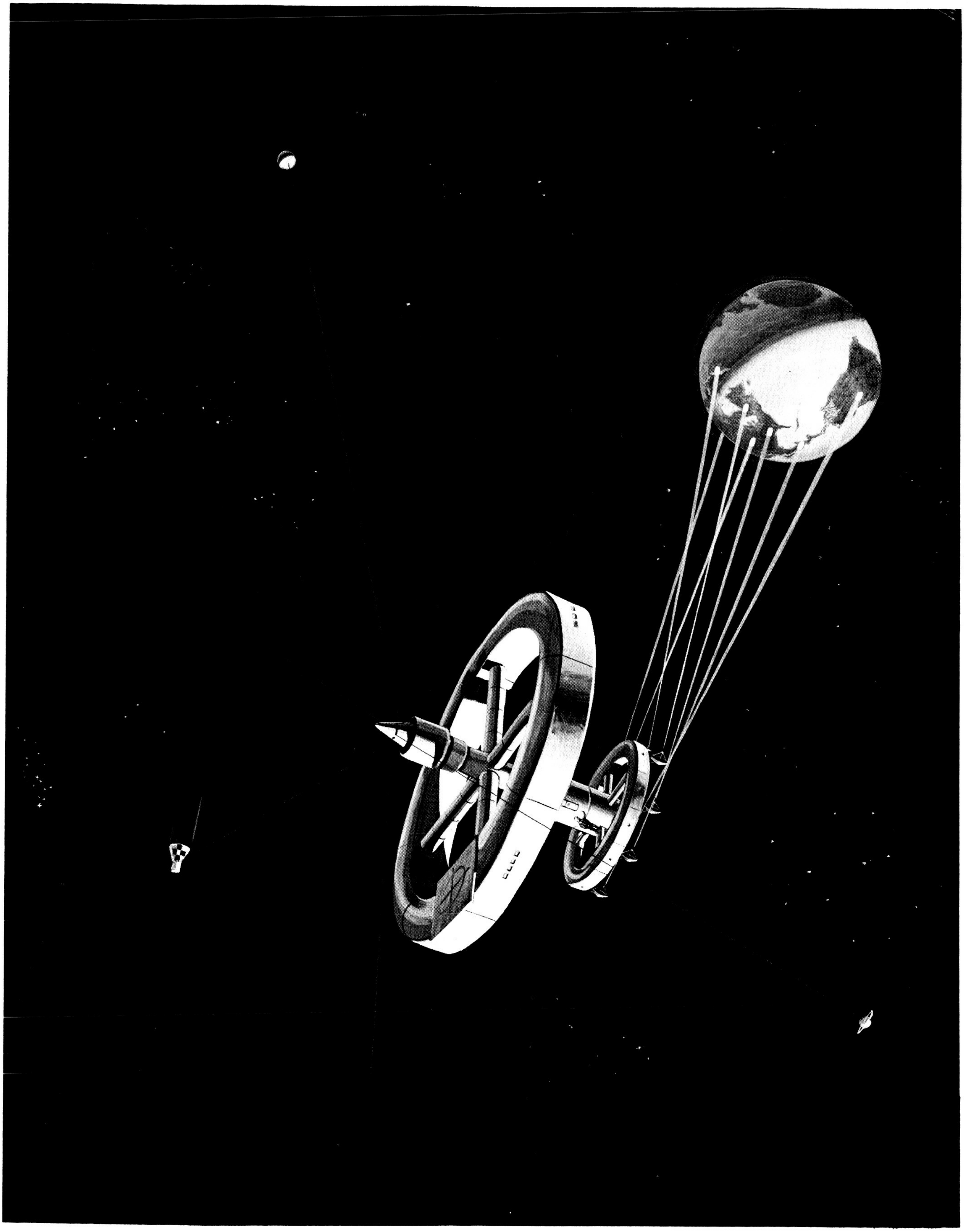
TRANSMISSION LOSS
(BETWEEN DIRECTIVE ANTENNAS)



ANTENNA RELATIONS

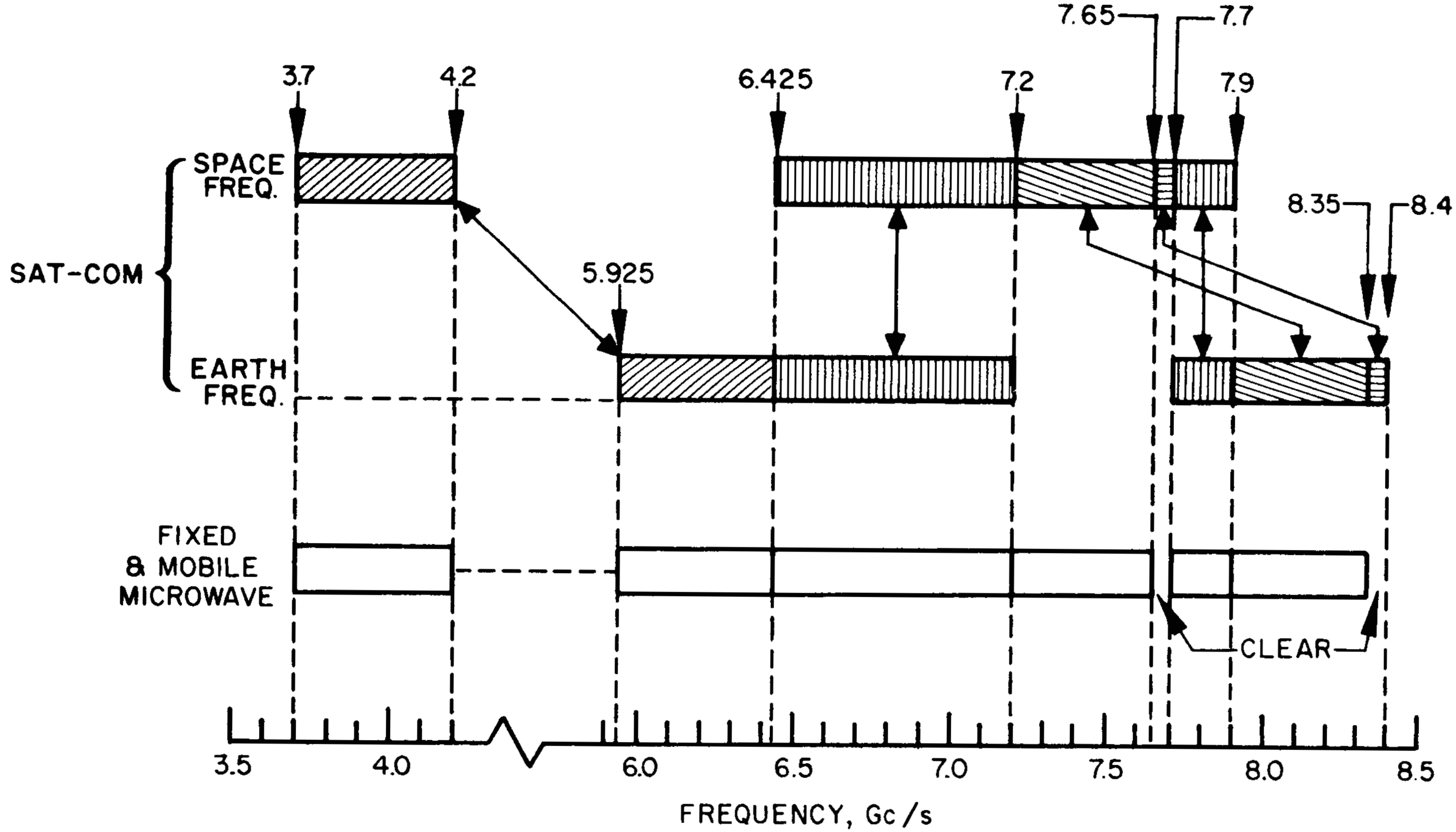


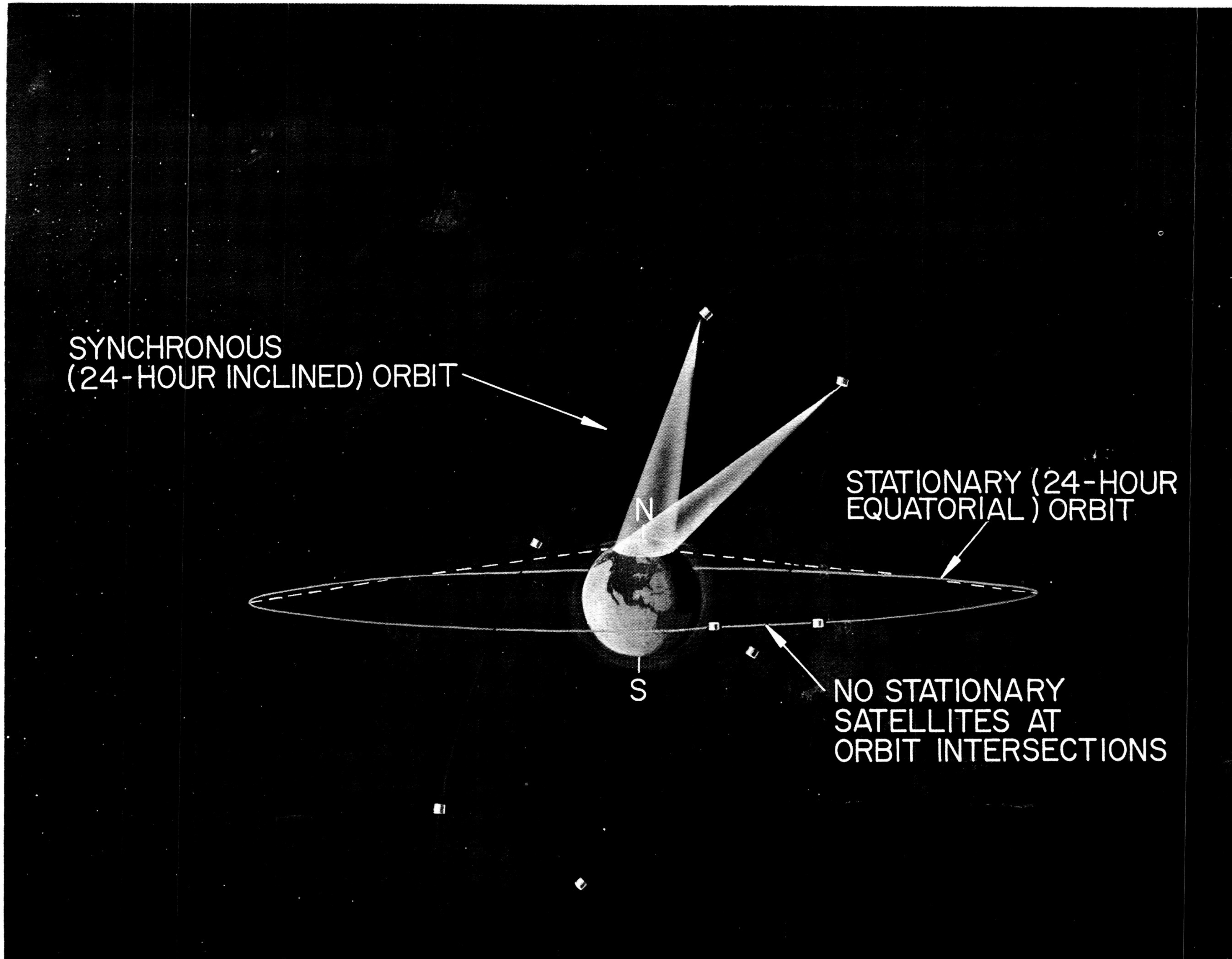


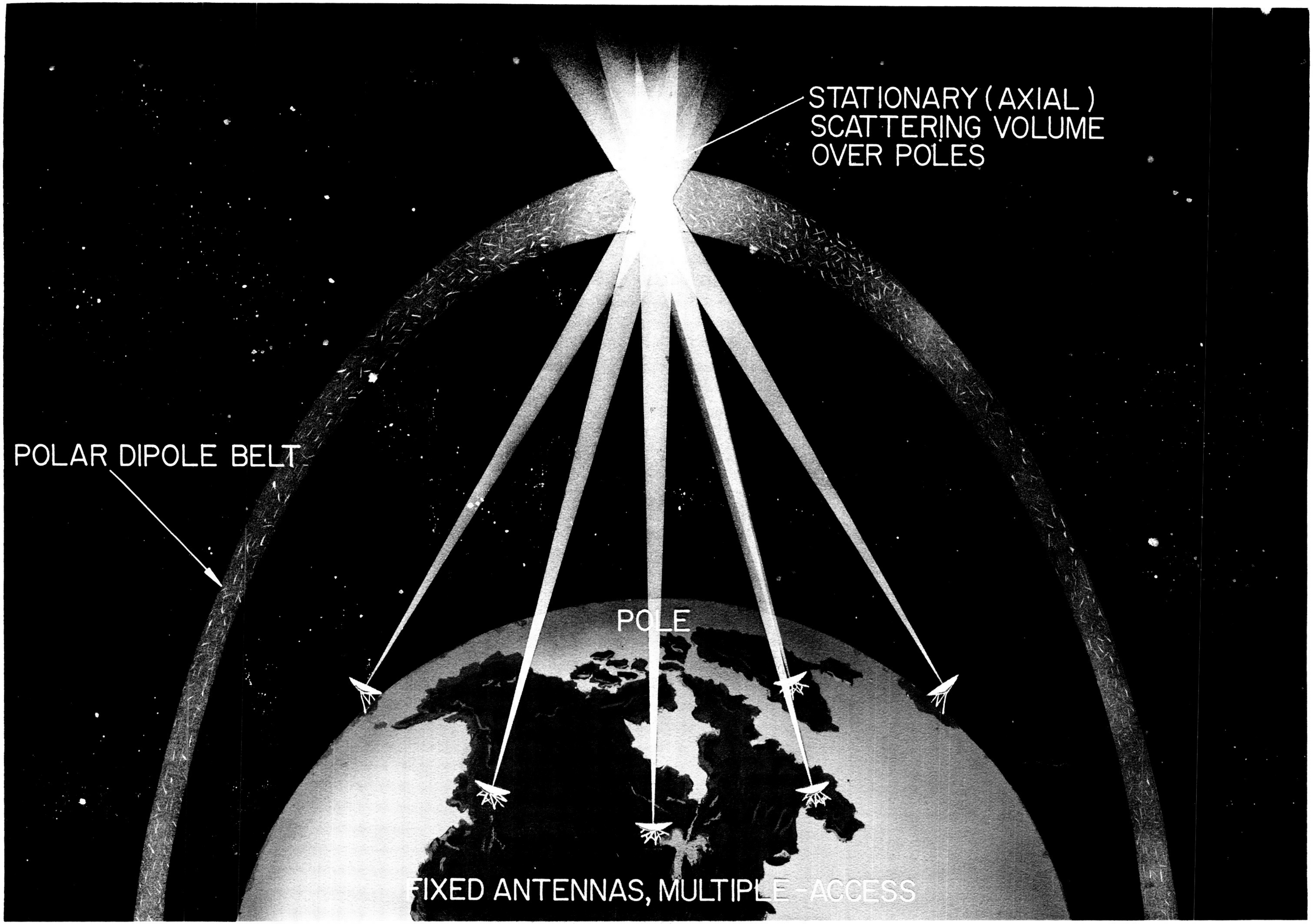


PROPOSED FREQUENCY ALLOCATIONS FOR SPACE COMMUNICATION

A-14/25




SYNCHRONOUS
(24-HOUR INCLINED) ORBIT
STATIONARY (24-HOUR
EQUATORIAL) ORBIT
N
S
NO STATIONARY
SATELLITES AT
ORBIT INTERSECTIONS


STATIONARY (AXIAL) SCATTERING VOLUME OVER POLES
POLAR DIPOLE BELT
POLE
FIXED ANTENNAS, MULTIPLE-ACCESS

ILLUSTRATIVE EARTH STATION COST COMPARISON

RANDOM – ORBIT	STATIONARY ORBIT
3 FULL–TRACKING ANTENNAS AT ~ $1,200,000 EACH FIXED COSTS ~ $5,000,000 (MOSTLY ANTENNA SYSTEM COSTS)	<u>ONE</u> FIXED ANTENNA AT ~ $20,000 FIXED COSTS ~ $100,000 (MOSTLY OTHER COSTS)

PER CIRCUIT COST (MULTIPLEXING, ETC.) ~ $5,000/CKT

FOR 1000 CIRCUITS: $5,000,000 + 1000 × $5,000 = $10,000,000 OR $10,000 PER CIRCUIT FOR <u>ONE</u> CIRCUIT, $5,005,000!	FOR ONLY 20 CIRCUITS: $100,000 + 20 × $5,000 = $200,000 OR SAME $10,000/CKT FOR ONE, ONLY $105,000

CONCLUSION

REQUIRES HEAVY TRAFFIC TERMINALS, <u>IN PAIRS</u>. MULTIPLE ACCESS BECOMES TOO EXPENSIVE.	LIGHT TRAFFIC TERMINALS ARE ECONOMICAL, HENCE MANY SHOULD USE EACH SATELLITE, WITH MULTIPLE ACCESS.